Deriving the Age of an Individual WD: SDSS, Bok, USNO, and Bayes

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Abstract. We report on ancient white dwarfs found in the proper motion survey we are conducting at the Bok and USNO telescopes. To date we have surveyed approximately 2800 square degrees of sky and identified numerous WDs with Teff $\leq$ 6000. A subset of these WDs are high velocity objects that most likely belong to the Galactic halo population. Where possible, we are acquiring trigonometric parallaxes to constrain the WD masses. We apply a new Bayesian modeling approach to these WDs that consistently incorporates precursor evolutionary timescales, the initial-final mass relation, WD interior and atmosphere models, and uses the observed magnitudes, distances, etc. to derive the distribution of WD age as a function of uncertainties in the observational parameters.

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INTRODUCTION

Cool White Dwarf Survey

We are searching for and then measuring the properties of cool white dwarfs (WDs) in order to determine the ages and star formation histories of the Galactic disk, thick disk, and halo. Yet WDs cooler than ~7000 K are difficult to identify in a survey because they cannot be separated from the much more abundant field main sequence stars based on photometry alone. Proper motion offers an efficient means of overcoming this obstacle. Reduced proper motion, defined as H = m + 5 log μ + 5, has long been used as a proxy for absolute magnitude for samples with similar kinematics. Munn et al. (2004) used the SDSS and USNO-B astrometry to derive proper motions with an accuracy of 3.5 mas yr^{-1}. Follow-up spectroscopy of high proper motion targets at the MMT, HET, and the McDonald 2.7m telescope have shown that WDs occupy a locus in the reduced proper motion diagram cleanly separated from most main sequence stars as

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14. ABSTRACT
We report on ancient white dwarfs found in the proper motion survey we are conducting at the Bok and USNO telescopes. To date we have surveyed approximately 2800 square degrees of sky and identified numerous WDs with Teff ≤ 6000. A subset of these WDs are high velocity objects that most likely belong to the Galactic halo population. Where possible, we are acquiring trigonometric parallaxes to constrain the WD masses. We apply a new Bayesian modeling approach to these WDs that consistently incorporates precursor evolutionary timescales, the initial-final mass relation, WD interior and atmosphere models, and uses the observed magnitudes, distances, etc. to derive the distribution of WD age as a function of uncertainties in the observational parameters.

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well as other astronomical flotsam with contamination of only a few percent (Kilic et al. 2006). Harris et al. (2006) used this result to create statistically complete catalogs of WDs and published a substantially improved disk luminosity function including 6000 WD candidates. This luminosity function is incomplete for the faintest and coolest WDs and so we have conducted a wide-field astrometric survey with a depth equal to the SDSS in order to provide a deeper second epoch match to the SDSS. We have been collecting astrometric data at the University of Arizona's 2.3m Bok telescope at Kitt Peak and at the USNO's 1.3m automated telescope near Flagstaff.

Bayesian Approach to Data Analysis

Because we have put so much effort into finding cool WDs and measuring their properties, we also wanted to improve our ability to compare WD models to our data. We have developed a powerful new Bayesian analysis package (von Hippel et al. 2006; DeGennaro et al. 2009; van Dyk et al. 2009) that compares stellar evolution models to photometry for star clusters, binaries, or single stars in any combination of photometric bands for which there are data and models. Our software accounts for individual errors for every data point, ancillary data such as distance from stellar parallax, and it can easily incorporate information such as stellar mass estimates from spectroscopic binaries or WD atmospheric analyses. Our Bayesian analysis package uses a technique known as Markov chain Monte Carlo to derive the posterior probability distribution for each parameter or combination of parameters of interest (e.g., age, distance, reddening, and stellar mass) taking account of the uncertainties in every other parameter of interest. We derive these posterior distributions for a range of input stellar evolution models (e.g., Dotter et al. (2008), Girardi et al. (2000), or Yi et al. (2001) isochrones and the WD models of Wood (1992) and Bergeron et al. (1995)).

RESULTS

Kilic et al. (2010) have just published spectral types, optical (*ugriz*) photometry, and near-IR (*JHK*) photometry for 126 cool white dwarfs, many of which were identified in our surveys. We have performed a preliminary Bayesian analysis of each of these stars. Our Bayesian approach is substantially different from the standard WD analysis. Typically, one fits the observed spectral energy distribution (SED) with a model atmosphere and derives the atmospheric type, effective temperature, and surface gravity. The surface gravity can in turn yield the WD mass. In cases where the surface gravity cannot be determined, distances from trigonometric parallaxes or stellar cluster membership can be used to derive stellar radii and thereby WD masses. The result is that the observations typically yield some combination of three parameters: effective temperature, log(g) or mass, and distance.

Our analysis uses precursor models, an initial-final mass relation (IFMR), WD cooling models, and WD atmosphere models to yield a different set of three parameters: WD age, WD mass or precursor mass, and distance. In Figure 1, we present results for a representative cool WD, J0003-0111. Each plotted point is an acceptable fit of the

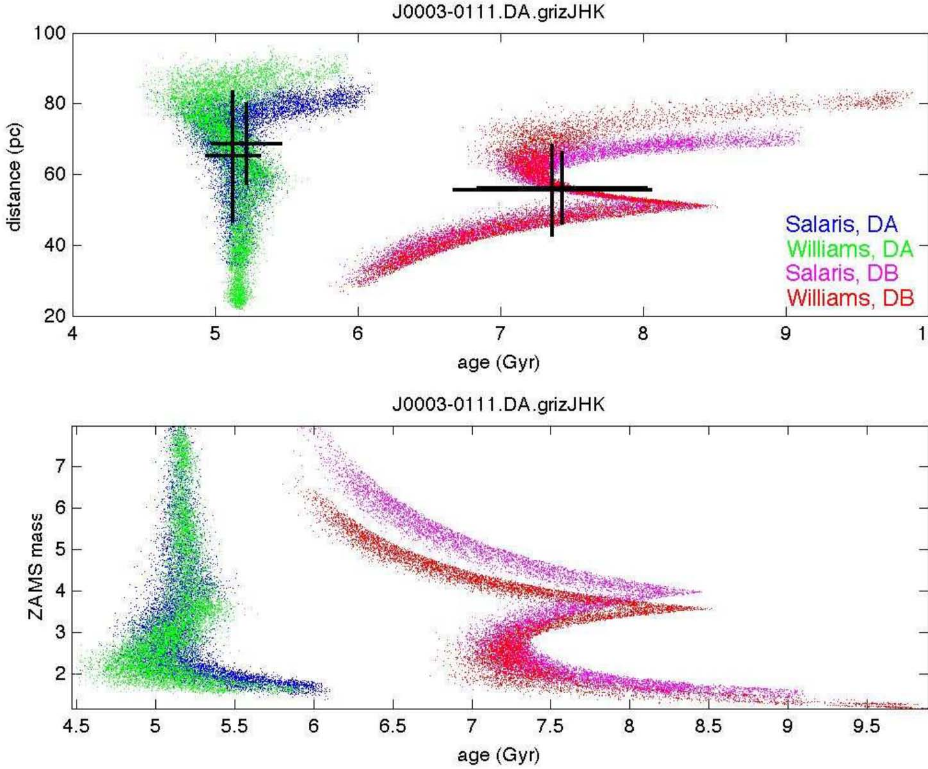

FIGURE 1. The WD J0003-0111 analyzed under four different combinations of atmospheric and IFMR assumptions. The horizontal axis indicates the total WD plus precursor age and the vertical axis indicates the distance in parsecs (top) or the precursor mass (bottom). The blue and green points located between 5 and 6 Gyr are for the DA assumption with the Salaris et al. (2009) and Williams et al. (2008) IFMRs, respectively. The magneta and red points in the more pronounced backward question mark shape between 6 and 10 Gyr are for the DB assumption with the Salaris and Williams IFMRs, respectively.

parameters of age, distance, and WD or precursor mass to the photometry (*grizJHK*). We did not include the *u*-band photometry, as recommended for these cool WDs when applying Bergeron et al. (1995) model atmospheres. This WD is a DA, but for presentation purposes, it was analyzed either as a DA or a DB as well as with two modern IFMRs (Salaris et al. 2009; Williams et al. 2008). Clearly the parameters of age, distance, and mass are correlated in a complicated manner. The overplotted black points indicate the means and standard deviations for each of these four cases, driving home the point that these distributions are very far from Gaussian. Our analysis also allows us to determine the dominant causes for structure in these parameter correlations. In the top panel of Figure 1, for example, the three components of the backward question mark

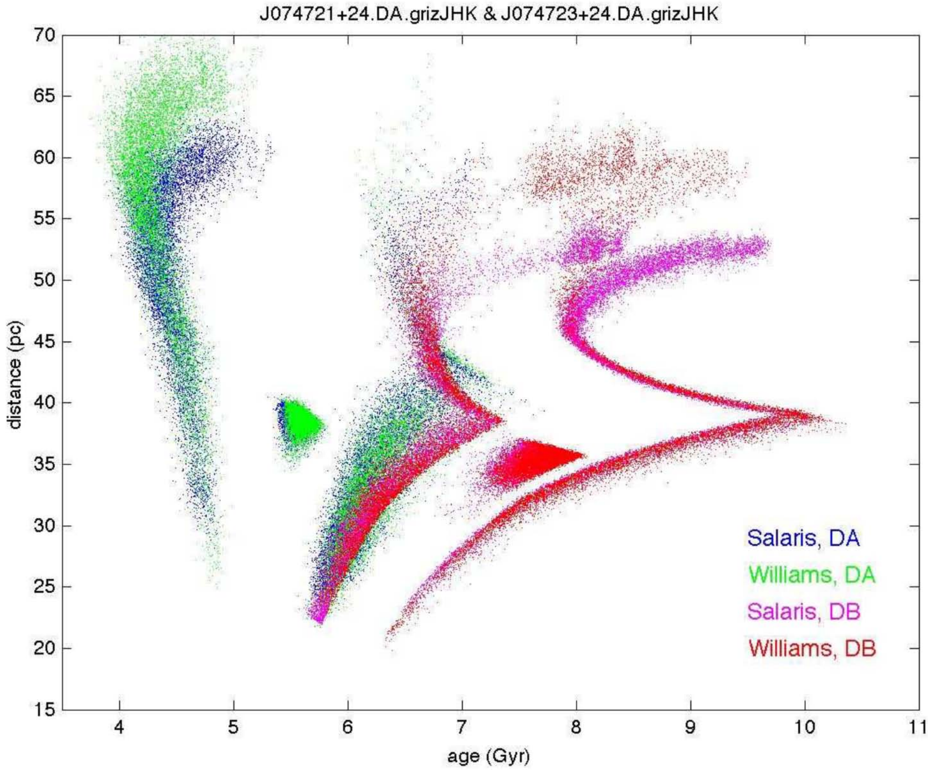

FIGURE 2. Similar to Figure 1, but now for a binary pair of WDs analyzed either individually (the backward question mark shape distributions) or together (the small triangle distributions centered on 5.5 and 7.5 Gyrs. The DA models for the stars analyzed individually are centered at 4.5 and 6.5 Gyrs and the DB models for the stars analyzed individually are centered at 7 and 8.5 Gyrs. The compact triangular distributions centered at 5.5 and 7.5 Gyrs are for the DA and DB assumptions for the stars analyzed as a binary.

shape are dominated by (from top to bottom): precursor ages, standard WD cooling, and WD crystallization effects.

In Figure 2, we present our results for the binary WD J074721+24 and J0747423+24. Both stars are DAs (Kilic et al. 2010), though we again analyze each as if it were a DA or a DB for illustrative purposes. The resulting parameter distributions are broadly similar to those for J0003-0111 in Figure 1. We then analyzed this pair with the requirement that they have a common distance and age, as is appropriate for this non-contact binary. These latter assumptions drastically collapse the available parameter space and the stars fit only within a small age distribution around 5.5 Gyrs at 35–40 pc (DA assumption) or 7.5 Gyrs at ∼35 pc (DB assumption). Interestingly, neither of these solutions overlaps

with the solution spaces for the stars analyzed individually. In this case, the Bayesian software ended up using the latitude provided by errors in the photometry and the fits correspond to different SEDs for the binary and individual cases.

CONCLUSIONS

We are obtaining a large quantity of new spectroscopy and photometry for cool WDs. We are analyzing these data with a sophisticated Bayesian software suite that allows us to estimate the masses, distances, and ages of these WDs, as well as correlations in these parameters. We are performing these analyses for a range of model assumptions in order to understand the effects of the standard model ingredients. We derive individual WD ages for a number of cool WDs, although these ages are not simple numbers but rather complicated, correlated distributions. In some cases, we expect that our further efforts at obtaining trigonometric parallaxes will allow us to refine the ages and test the model ingredients for a number of these WDs.

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